

Detection Prospects of the Cosmic Neutrino Background

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The existence of the cosmic neutrino background (CνB) is a fundamental prediction of the standard Big Bang cosmology. Although current cosmological probes provide indirect observational evidence, the direct detection of the CνB in a laboratory experiment is a great challenge to the present experimental techniques. We discuss the future prospects for the direct detection of the CνB, with the emphasis on the method of captures on beta-decaying nuclei and the PTOLEMY project. Other possibilities using the electron-capture (EC) decaying nuclei, the annihilation of extremely high-energy cosmic neutrinos (EHECνs) at the Z -resonance, and the atomic de-excitation method are also discussed in this review.

Keywords: CνB; Direct detection, Beta decay.

1. Introduction

As weakly-interacting and rather stable particles, relic neutrinos were decoupled from radiation and matter at a temperature of about one MeV and an age of one second after the Big Bang¹. It is quite similar to the cosmic microwave background (CMB) radiation, whose formation was at a time of around 3.8×10^5 years after the Big Bang. This cosmic neutrino background (CνB) played an important role in the evolution of the Universe, and its existence has been indirectly proved from current cosmological data on the Big Bang nucleosynthesis (BBN), large-scale structures of the cosmos and CMB anisotropies².

The properties of the CνB are tightly related to the properties of the CMB. In particular, in the absence of lepton asymmetries the temperature and average number density of relic neutrinos can be expressed as¹

$$T_\nu = \left(\frac{4}{11} \right)^{1/3} T_\gamma \approx 1.945 \text{ K}, \quad n_\nu = \frac{9}{11} n_\gamma \approx 336 \text{ cm}^{-3}. \quad (1)$$

As a consequence, one predicts the average three-momentum today for each species of the relic neutrino is very small³:

$$\langle p_\nu \rangle = 3T_\nu \approx 5.8 \text{ K} \approx 5 \times 10^{-4} \text{ eV}, \quad (2)$$

implying that at least two mass eigenstates of relic neutrinos are already non-relativistic, no matter whether the neutrino mass spectrum is the normal or inverted hierarchy.

Although cosmological observations provide the indirect evidence for the existence of the CνB, direct detection in a laboratory experiment is a great challenge to the present experimental techniques. Among several possibilities³, the most promising one seems to be the neutrino capture experiment using radioactive β -decaying nuclei^{4–13}. The proposed PTOLEMY project¹⁴ aims to obtain the sensitivity required to detect the CνB using 100 grams of ^3H as the capture target. Other interesting possibilities include the electron-capture (EC) decaying nuclei^{15–18}, the annihilation of extremely high-energy cosmic neutrinos (EHECνs) at the Z -resonance^{19–21}, and the atomic de-excitation method²².

The remaining parts of this work are organized as follows. In Sec. 2 we introduce the method of captures on the beta-decaying nuclei and calculate the β -decay energy spectrum and the relic neutrino capture rate. Sec. 3 is devoted to flavor effects of the relic neutrino capture spectrum. We shall present a brief description on other interesting possibilities of the CνB detection in Sec. 4, and then conclude in Sec. 5.

2. Captures on the Beta-decaying Nuclei

In the presence of $3 + n$ species of active and sterile neutrinos, the flavor eigenstates of three active neutrinos and n sterile neutrinos can be written as^{1,2}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}, \quad (3)$$

where ν_i is a mass eigenstate of active (for $1 \leq i \leq 3$) or sterile (for $4 \leq i \leq 3 + n$) neutrinos, and $U_{\alpha i}$ stands for an element of the $(3 + n) \times (3 + n)$ neutrino mixing matrix.

One of the most promising method to measure the absolute electron neutrino mass is the nuclear β -decay

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}'(A, Z + 1) + e^- + \bar{\nu}_e, \quad (4)$$

where A and Z are the mass and atomic numbers of the parent nucleus, respectively. The differential decay rate of a β -decay can be written as²³

$$\begin{aligned} \frac{d\lambda_\beta}{dT_e} &= \int_0^{Q_\beta - \min(m_i)} dT'_e \left\{ \frac{G_F^2 \cos^2 \theta_C}{2\pi^3} F(Z, E_e) |\mathcal{M}|^2 E_e \sqrt{E_e^2 - m_e^2} \right. \\ &\quad \times (Q_\beta - T'_e) \sum_{i=1}^4 \left[|U_{ei}|^2 \sqrt{(Q_\beta - T'_e)^2 - m_i^2} \Theta(Q_\beta - T'_e - m_i) \right] \left. \right\} \\ &\quad \times R(T_e, T'_e), \end{aligned} \quad (5)$$

where $T'_e = E_e - m_e$ denotes the intrinsic kinetic energy of the outgoing electron, $F(Z, E_e)$ is the Fermi function, $|\mathcal{M}|^2$ is the dimensionless nuclear matrix elements²³,

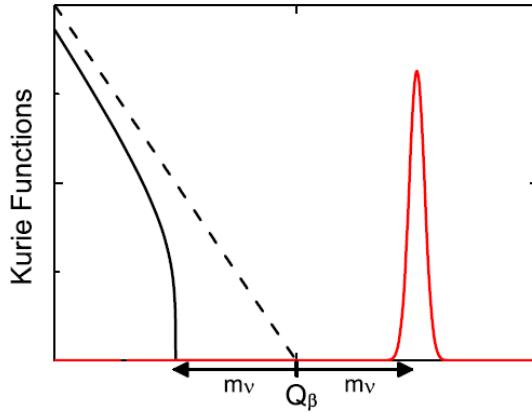


Fig. 1. Idealized electron spectra for the tritium beta decay and relic neutrino capture. The dashed and black-solid lines are shown for β -decay spectra of the massless and massive neutrinos respectively. The red-solid line with the sharp peak is for the relic neutrino signal.

and $\theta_C \simeq 13^\circ$ is the Cabibbo angle. Note that a Gaussian energy resolution function,

$$R(T_e, T'_e) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(T_e - T'_e)^2}{2\sigma^2}\right], \quad (6)$$

is implemented in Eq. (5) to include the finite energy resolution, and the theta function is adopted to ensure the kinematic requirement. The spectral shape near the β -decay endpoint represents a kinetic measurement of the absolute neutrino masses, which can be understood by comparing the dashed and black solid lines of Fig. 1. The gap between end points of two black lines stands for a measurement of the effective electron neutrino mass.

On the other hand, the threshold-less neutrino capture process,

$$\nu_e + \mathcal{N}(A, Z) \rightarrow \mathcal{N}'(A, Z + 1) + e^-, \quad (7)$$

is located well beyond the end point of the β -decay, where the signal is characterized by the monoenergetic kinetic energy of the electron for each neutrino mass eigenstate. A measurement of the distance between the decay and capture processes will directly probe the C ν B and constrain or determine the masses and mixing angles. The differential neutrino capture rate of this process reads

$$\frac{d\lambda_\nu}{dT_e} = \sum_i |U_{ei}|^2 \sigma_{\nu_i} v_{\nu_i} n_{\nu_i} R(T_e, T'_e), \quad (8)$$

where the sum is for all the neutrino mass eigenstates and

$$n_{\nu_i} = \frac{n_{\nu_i}}{\langle n_{\nu_i} \rangle} \cdot \langle n_{\nu_i} \rangle \equiv \zeta_i \cdot \langle n_{\nu_i} \rangle, \quad (9)$$

denotes the number density of the relic neutrinos ν_i around the Earth. The standard Big Bang cosmology gives the prediction $\langle n_{\nu_i} \rangle \approx \langle n_{\bar{\nu}_i} \rangle \approx 56 \text{ cm}^{-3}$ for each species

of active neutrinos, and the prediction is also expected to hold for each species of sterile neutrinos if they could be fully thermalized in the early Universe. The number density of relic neutrinos around the Earth may be enhanced by the gravitational clustering effect (i.e., the factor ζ_i) when the neutrino mass is larger than 0.1 eV²⁴. In Eq. (7) the capture cross-section times neutrino velocity can be written as

$$\sigma_{\nu_i} v_{\nu_i} = \frac{2\pi^2}{A} \cdot \frac{\ln 2}{T_{1/2}}, \quad (10)$$

where A is the nuclear factor characterized by Q_β and Z , and $T_{1/2}$ is the half-life of the parent nucleus.

Considering the running time and target mass of a particular experiment, the distributions of the numbers of capture signal and β -decay background events are expressed, respectively, as

$$\begin{aligned} \frac{dN_S}{dT_e} &= \frac{1}{\lambda_\beta} \cdot \frac{d\lambda_\nu}{dT_e} \cdot \frac{\ln 2}{T_{1/2}} \bar{N}_T t, \\ \frac{dN_B}{dT_e} &= \frac{1}{\lambda_\beta} \cdot \frac{d\lambda_\beta}{dT_e} \cdot \frac{\ln 2}{T_{1/2}} \bar{N}_T t, \end{aligned} \quad (11)$$

where \bar{N}_T is the averaged number of target atoms for a given exposure time t . Therefore, $\bar{N}_T t$ gives the total target factor in the experiment:

$$\bar{N}_T t = N(0) \cdot \frac{T_{1/2}}{\ln 2} \cdot \left(1 - e^{-t \cdot \frac{\ln 2}{T_{1/2}}} \right), \quad (12)$$

with $N(0)$ being the initial target number at $t = 0$.

To get a better signal-to-background ratio, one can investigate different kinds of candidate nuclei by considering factors of the cross-section, half-life, β -decay rate, and the detector energy resolution. The target nuclei should have the half-life $T_{1/2}$ longer than duration of the exposure time, have the maximal possible cross-section times neutrino velocity, and have the minimal possible background rate. An exhaustive survey was done several years ago⁶, and a summary of several candidates of the β^- -decaying nuclei is shown in Tab. 1, from which one can find ³H, ¹⁰⁶Ru, and ¹⁸⁷Re can be possible promising nuclei.

Table 1. Several candidates of the β^- -decaying nuclei⁶.

Isotope	Q_β (keV)	Decay type	Half-life (sec)	$\sigma_{\nu_i} \cdot v_{\nu_i}$ (10^{-41} cm 2)
³ H	18.591	β^-	3.8878×10^8	7.84×10^{-4}
⁶³ Ni	66.945	β^-	3.1588×10^9	1.38×10^{-6}
⁹³ Zr	60.63	β^-	4.952×10^{13}	2.39×10^{-10}
¹⁰⁶ Ru	39.4	β^-	3.2278×10^7	5.88×10^{-4}
¹⁰⁷ Pd	33	β^-	2.0512×10^{14}	2.58×10^{-10}
¹⁸⁷ Re	2.64	β^-	1.3727×10^{18}	4.32×10^{-11}

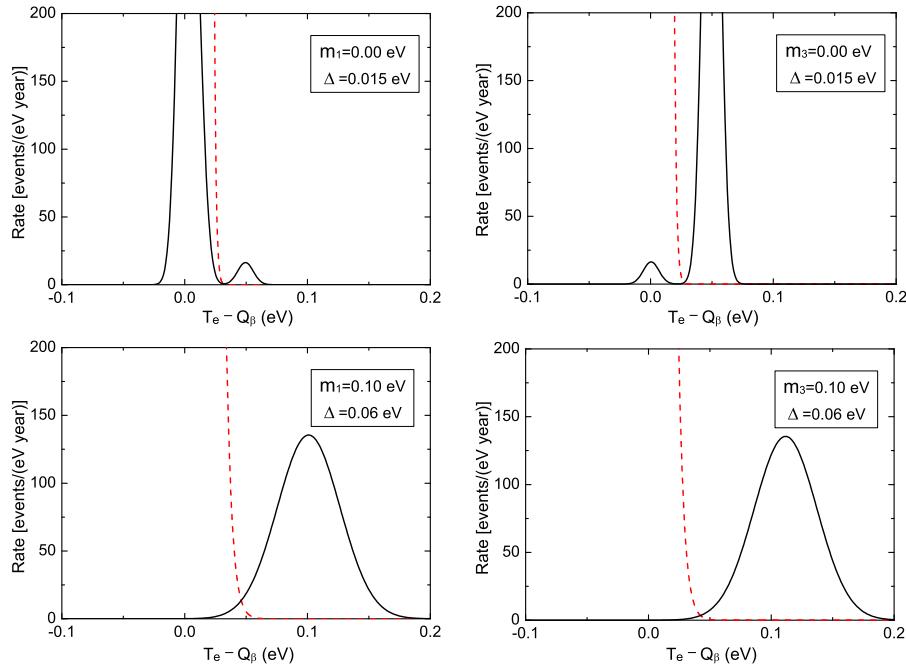


Fig. 2. The relic neutrino capture rate as a function of the kinetic energy of electrons in the standard scheme with $\Delta m_{31}^2 > 0$ (left panel) or $\Delta m_{31}^2 < 0$ (right panel). The gravitational clustering of three active neutrinos has been neglected for simplicity.

The β -decay experiments of current generation includes the spectrometer of KATRIN²⁵ and the calorimeter of MARE²⁶. KATRIN uses 50 μg of ^3H as the effective target mass, and MARE is planning to deploy 760 grams of ^{187}Re . Therefore, we can estimate the $\text{C}\nu\text{B}$ event rates, respectively, as

$$N^\nu(\text{KATRIN}) \simeq 4.2 \times 10^{-6} \times \sum_i |U_{ei}|^2 \zeta_i \text{ yr}^{-1}, \quad (13)$$

$$N^\nu(\text{MARE}) \simeq 7.6 \times 10^{-8} \times \sum_i |U_{ei}|^2 \zeta_i \text{ yr}^{-1}. \quad (14)$$

Moreover, a realistic proposal for the $\text{C}\nu\text{B}$ detection is the PTOLEMY project¹⁴, which is designed to employ 100 grams of ^3H as the capture target using a combination of a large-area surface-deposition tritium target, the MAC-E filter, the RF tracking, the time-of-flight systems, and the cryogenic calorimetry. Finally, the event rate of PTOLEMY are calculated to reach the observable level:

$$N^\nu(\text{PTOLEMY}) \simeq 8.0 \times \sum_i |U_{ei}|^2 \zeta_i \text{ yr}^{-1}. \quad (15)$$

3. Flavor Effects

Besides the total capture rates, the $\text{C}\nu\text{B}$ detection exhibits interesting properties of flavor effects due to the neutrino mixing. In this section, we shall discuss the effects

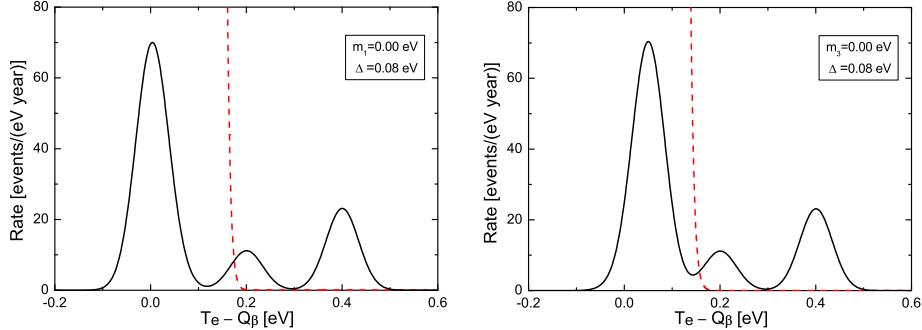


Fig. 3. The capture rate of the $C\nu B$ as a function of the electron's kinetic energy in the (3+2) mixing scheme with $\Delta m_{31}^2 > 0$ (left panel) and $\Delta m_{31}^2 < 0$ (right panel)¹⁰. The gravitational clustering of relic sterile neutrinos around the Earth has been illustrated by taking $\zeta_1 = \zeta_2 = \zeta_3 = 1$ and $\zeta_5 = 2\zeta_4 = 10$ for example.

of the neutrino mass hierarchy, presence of light sterile neutrinos²⁷, and keV sterile neutrinos as a candidate of warm dark matter²⁹.

In our calculation, we adopt best-fit values of the relevant three-neutrino oscillation parameters (i.e., θ_{12} , θ_{13} , Δm_{21}^2 and $|\Delta m_{31}^2|$) from Review of Particle Physics², and all the other parameters will be explicitly mentioned when needed. Our default assumption of the target mass is 100 grams of 3H , but will be 10 kg of 3H or 1 ton of ^{106}Ru when we discuss the keV sterile neutrinos.

Fig. 2 shows the capture rate of the $C\nu B$ as a function of the kinetic energy T_e of electrons in the standard three-neutrino scheme with $\Delta m_{31}^2 > 0$ (left panel) and $\Delta m_{31}^2 < 0$ (right panel). The finite energy resolution Δ (i.e., $\Delta = 2\sqrt{2 \ln 2} \sigma$) is taken in such a way that only one single peak can be observed beyond the β -decay background. The gravitational clustering of three active neutrinos has been neglected for simplicity. As the lightest neutrino mass (m_1 in the left panel or m_3 in the right panel) increases from 0 to 0.1 eV, the neutrino capture signal moves towards the larger T_e region. Hence the distance between the signal peak and the β -decay background becomes larger for a larger value of the lightest neutrino mass, and therefore the required energy resolution is less stringent. Comparing between the left panel and right panel, one can observe that it is easier to detect the $C\nu B$ in the $\Delta m_{31}^2 < 0$ case, where the capture signal is separated more apparently from the β -decay background. The reason is that the dominant mass eigenstates ν_1 and ν_2 in ν_e have greater eigenvalues than in the $\Delta m_{31}^2 > 0$ case.

Next we are going to study the (3+2) mixing scheme with two light sterile neutrinos. Considering the hints of short baseline oscillations^{27,28}, we assume $m_4 = 0.2$ eV and $m_5 = 0.4$ eV together with $|U_{e1}| \approx 0.792$, $|U_{e2}| \approx 0.534$, $|U_{e3}| \approx 0.168$, $|U_{e4}| \approx 0.171$ and $|U_{e5}| \approx 0.174$ in the numerical calculations. We also take $m_1 = 0$ or $m_3 = 0$ for simplicity. We illustrate the capture rate of the $C\nu B$ as a function of the electron's kinetic energy T_e against the corresponding β -decay background for both $\Delta m_{31}^2 > 0$ and $\Delta m_{31}^2 < 0$ schemes in Fig. 3. To take account

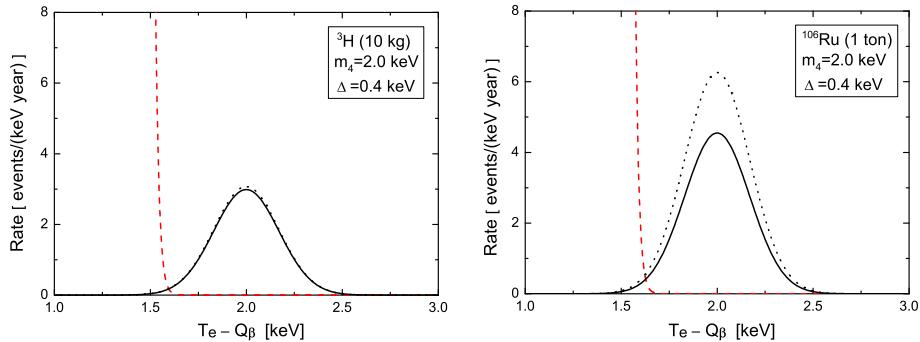


Fig. 4. The keV sterile neutrino capture rate as a function of the kinetic energy of electrons with ^3H (left panel) and ^{106}Ru (right panel) as our target sources¹¹. The solid (or dotted) curves denote the signals with (or without) the half-life effect.

of possible gravitational clustering effects, we assume $\zeta_1 = \zeta_2 = \zeta_3 = 1$ (without clustering effects for three active neutrinos) and $\zeta_5 = 2\zeta_4 = 10$ (with mild clustering effects for two sterile neutrinos). As one can see from Fig. 3, the signals of sterile neutrinos are obviously enhanced because of $\zeta_4 > 1$ and $\zeta_5 > 1$. If the overdensity of relic neutrinos is very significant around the Earth, it will be helpful for the CνB detection through the neutrino capture process.

Finally we want to talk about the detection of keV sterile neutrinos as a candidate of warm dark matter. We shall work in the (3+1) mixing scheme, where the mixing element and mass of the sterile neutrino are severely constrained by cosmological observational data²⁹. Here $m_4 = 2$ keV and $|U_{e4}|^2 \simeq 5 \times 10^{-7}$ are assumed for illustration. We also take $\Delta m_{31}^2 > 0$ and $m_1 = 0$ for simplicity. From the mass density of dark matter around the Earth²⁹, (i.e., $\rho_{\text{DM}}^{\text{local}} \simeq 0.3 \text{ GeV cm}^{-3}$), we can calculate the number density of ν_4 as

$$n_{\nu_4} \simeq 10^5 \times \frac{3 \text{ keV}}{m_4} \text{ cm}^{-3}. \quad (16)$$

Our numerical calculations are presented in Fig. 3, where two isotope sources (i.e., 10 kg ^3H and 1 ton ^{106}Ru) are illustrated for comparison. One can notice that the required energy resolution is not a problem because of the larger sterile neutrino mass. However, the extremely small active-sterile mixing makes the observability of keV sterile neutrinos rather dim and remote. We also show the half-life effects of both isotopes in Fig. 4. The finite lifetime is negligible for the ^3H nuclei, but important for the ^{106}Ru nuclei. It can reduce around 30% of the capture rate on ^{106}Ru . Hence the half-life effect must be considered if duration of the exposure time is comparable with the source half-life.

4. Other possibilities

The capture on the β -decaying nuclei is one of the most promising methods to detect directly the CνB. However, from Eq. (7) only neutrinos of the electron flavor

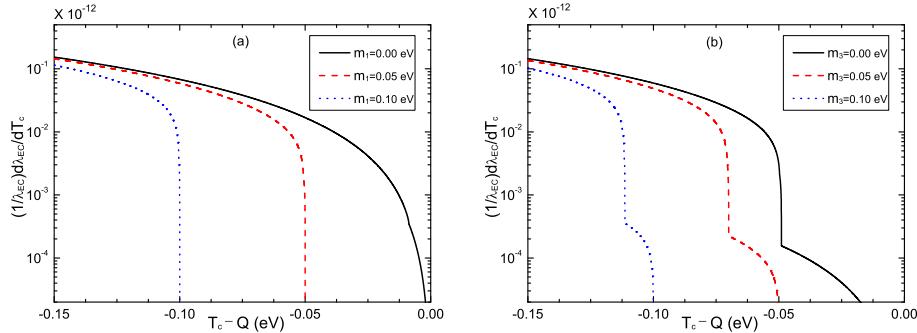


Fig. 5. The fine structure spectrum near the endpoint of the ^{163}Ho EC-decay in the $m_{31}^2 > 0$ (left panel) or $m_{31}^2 < 0$ (right panel) case¹⁷.

are relevant for this detection. Therefore, we should consider other possibilities for relic neutrinos of μ and τ flavors and antiparticles of the $C\nu B$.

Similar to the process of captures on β -decaying nuclei, the EC-decaying nuclei can be the target of relic antineutrino captures. Here we take the isotope ^{163}Ho as the working example^{15–18}. It should be stressed that the structure near the endpoint of the ^{163}Ho EC-decay spectrum is applicable to study the absolute neutrino masses in a similar way as the β -decay. We could distinguish between the inverted and normal mass hierarchies by comparing the right and left panels of Fig. 5. The properties of the relic antineutrino capture against the EC-decaying background are similar to those discussed in Sec. 2. As the order of magnitude estimate, one needs 30 kg ^{163}Ho to obtain one event per year for the relic antineutrino detection, and needs as much as 600 ton ^{163}Ho to get one event per year for the keV sterile antineutrino detection.

Another appealing possibility is the annihilation of EHEC ν s with the $C\nu B$ in the vicinity of Z -resonance^{19–21} (i.e., $\nu\bar{\nu} \rightarrow Z$). The resonance energy of EHEC ν s associated with each neutrino mass eigenstate can be calculated as

$$E_{0,i}^{\text{res}} = \frac{m_Z^2}{2m_i} \simeq 4.2 \times 10^{12} \left(\frac{1 \text{ eV}}{m_{\nu_i}} \right) \text{ GeV}, \quad (17)$$

where m_Z denotes the Z boson mass. Since the annihilation cross-section at the resonance is enhanced by several orders of magnitude compared to the non-resonant scattering. Therefore, the absorption dips at the resonance energies are expected for the EHEC ν s arriving at the Earth^{19–21}, which could provide the direct evidence for the existence of the $C\nu B$.

Recently there is another interesting method of the $C\nu B$ detection using the atomic de-excitation process²². The de-excitation process of metastable atoms into the emission mode of a single photon and a neutrino pair, is defined as the radiative emission of neutrino pair (RENP),

$$|e\rangle \rightarrow |g\rangle + \gamma + \nu_i + \nu_j, \quad (18)$$

where $|e\rangle$ and $|g\rangle$ are the respective initial and final states of the atoms, ν_i and ν_j are the neutrino mass eigenstates. The existence of the CνB may distort the photon energy spectrum because of the Pauli exclusion principle, which provides a possible promising way to detect the CνB²².

5. Conclusion

The standard Big Bang cosmology predicts the existence of a cosmic neutrino background formed at a temperature of about one MeV and an age of one second after the Big Bang. A direct measurement of the relic neutrinos would open a new window to the early Universe. In this review we have discussed the future prospects for the direct detection of the CνB, with the emphasis on the method of captures on β -decaying nuclei and the PTOLEMY project. We calculated the neutrino capture rate as a function of the kinetic energy of electrons against the corresponding β -decay background, and discussed the possible flavor effects including the neutrino mass hierarchy, light sterile neutrinos, and keV sterile neutrinos as a candidate of warm dark matter. Other possibilities using the EC-decaying nuclei, the annihilation of EHECνs at the Z -resonance, and the atomic de-excitation method are also presented in this review. We stress that such direct measurements of the CνB in the laboratory experiments might not be hopeless in the long term.

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